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Silica aerogel core waveguide

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Abstract: We have selectively filled the core of hollow photonic crystal fibre with silica aerogel. Light is guided in the aerogel core, with a measured attenuation of 0.2 dB/cm at 1540 nm comparable to that of bulk aerogel. The structure guides light by different mechanisms depending on the wavelength. At long wavelengths the effective index of the microstructured cladding is below the aerogel index of 1.045 and guidance is by total internal reflection. At short wavelengths, where the effective cladding index exceeds 1.045, a photonic bandgap can guide the light instead. There is a small region of crossover, where both index- and bandgap-guided modes were simultaneously observed.

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1. Introduction

We report single-mode light guidance in an aerogel core, hosted in a hollow-core photonic crystal fibre (PCF). Despite the low refractive index of the aerogel, the PCF cladding has an even lower effective index, allowing confinement by total internal reflection. It also mechanically protects and supports the aerogel core, which has a 6 μm diameter typical of single-mode cores.

Aerogel is a low-density, rigid, highly porous form of silica glass with an air-filling fraction typically between 86 and 98% [1]. The small scale of its structure (interconnected pores around 40 nm across between silica 'strings' ~ 5 nm thick) makes the aerogel a transparent effective medium with some Rayleigh-like scattering [1] and an extraordinarily low refractive index of 1.01–1.08 [2], well outside the range attainable with any other solid materials. It has been reported to have a Kerr nonlinearity five orders of magnitude greater

than that of solid silica [3], and it can be doped to provide gain, enhanced nonlinearity, plasmonic properties or a gas-permeable host for a volume distribution of nanoparticles [4].

To exploit such intensity-dependent interactions it would be advantageous to confine light to a small waveguide core made of aerogel. This allows interaction lengths limited by the attenuation of the material rather than, say, the Rayleigh length of a focused free-space beam. Hollow-core PCFs have been used to effect long-distance interactions with liquids and gases within the core [5], and can do likewise for aerogel. Furthermore, inhomogeneities that cause beam distortion in bulk aerogel will not compromise beam quality in a guided mode.

2. Aerogel

We made aerogel using a 1-step sol-gel process [2] with high-temperature supercritical drying to remove solvent. The molar ratio of tetramethoxysilane, trimethoxymethylsilane (MTMS), methanol, water and ammonia was 1: 0.11: 2: 4.5: 3.3×10^{-3} . The chemicals were mixed to form a fluid sol, which turned to a rigid wet-gel over ~40 minutes. Supercritical drying in methanol was carried out after 2 weeks of aging and two solvent exchange steps to remove excess water, to reduce the final aerogel shrinkage to less than 5%. The MTMS co-precursor makes the aerogel hydrophobic and able to support water droplets on the surface [6].

The refractive index of bulk aerogel fabricated this way was measured by scanning a laser beam across a surface of known curvature. The measured deflection of the beam corresponded to an index of 1.045 ± 0.005 . By way of confirmation the measured density of the aerogel was $0.19 \pm 0.01 \text{ g/m}^3$, giving an index of 1.0475 using a simple interpolative formula [2].

We measured the loss of similar aerogels supercritically dried after solvent exchange with liquid CO_2 [7]. Optical quality surfaces were made by casting the wet gel in PMMA cuvettes, then removing them before supercritical drying [4]. Figure 1 is a typical loss spectrum, dominated by Rayleigh scattering at visible wavelengths and various molecular resonances in the infrared. The minimum loss of this 1 cm sample was 0.06 dB at 1310 nm.

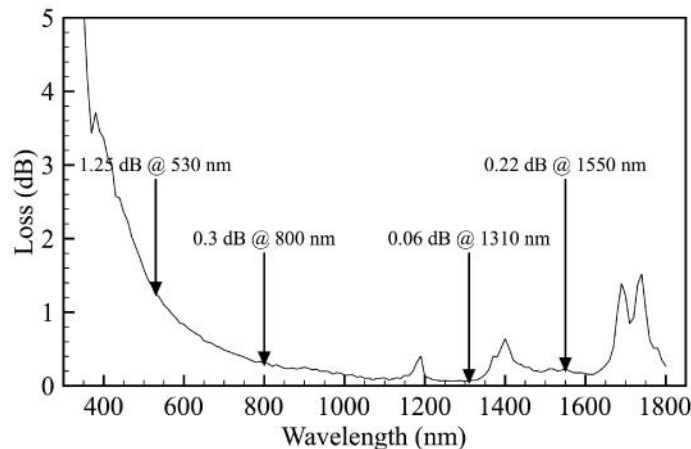


Fig. 1. Measured loss spectrum through 1 cm of silica aerogel.

3. Aerogel filled fibre

To form aerogel in the core of a hollow-core PCF, sol was sucked into one end of the fibre using a vacuum chamber at the other end. The unfilled fibre guided light by a photonic bandgap at visible wavelengths, and had a high air-filling fraction. To ensure that only the core was filled, one end of the PCF was heated in a fusion splicer to locally collapse the cladding holes but not the core, isolating the sol ends of the holes from the vacuum pump [8]. Alternatively, the core filled to a greater length than the cladding holes even if they weren't collapsed, so an exclusively core-filled length of ~30 cm could be cut away and the rest

disposed of. (Various other techniques could be employed to selectively fill different cladding holes [9, 10], for example to create coupled cores or tighter light confinement.)

After ~40 minutes of filling, the sol in the fibre turned to wet-gel, which was then aged and supercritically dried in methanol as described above. Although solvent exchange with liquid CO₂ would allow supercritical drying at a lower temperature and is less hazardous, the required timescale for diffusion along several cm of fibre is impractical.

The scanning electron micrographs (SEMs) of Fig. 2 show unfilled and core-filled fibres. Figure 2(c) shows the aerogel slightly proud of the PCF endface. This difference in cleaving planes was typical, and the aerogel was equally often recessed by a similar amount.

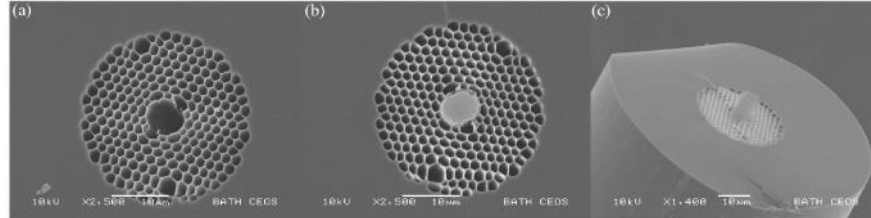


Fig. 2. SEMs of a hollow-core PCF with the core (a) empty and (b) filled with aerogel. (c) Tilted image of (b), where the aerogel core sticks out from the fibre.

The attenuation of the fibre was measured using the cutback technique. Light from a broadband LED source was coupled into ~20 cm of fibre using a 10 × microscope objective. The near-field pattern at the output was imaged on a linear infrared (InGaAs) camera through a succession of 10 nm bandpass filters in turn, checking that the light was in the core. The output was refocused for each wavelength but the input stayed fixed. Then 6.5 cm of fibre was cut off without disturbing the launch optics, and a new set of near-field images obtained. Since the camera was linear, the images could be used to calculate loss. The resulting spectrum is shown in Fig. 3; the minimum attenuation was 0.2 dB/cm at 1540 nm and there is a resonant loss at ~1400 nm, corresponding to vibration of OH bonds.

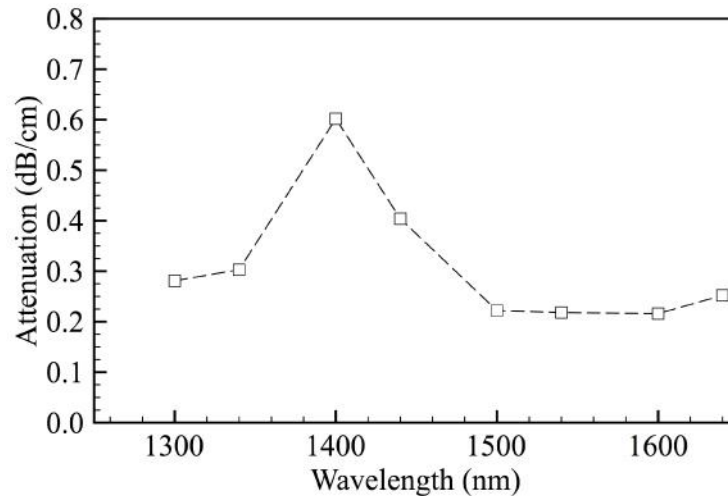


Fig. 3. Measured attenuation of the aerogel-filled fibre at 8 discrete wavelengths.

Figure 4(a) shows transmission spectra of similar lengths of aerogel-filled and unfilled fibre, measured using a supercontinuum source and an optical spectrum analyzer. The spectra are unnormalised because of differences in input coupling. The unfilled fibre has a transmission window at visible wavelengths due to its photonic bandgap, with a small amount of power at other wavelengths. The filled fibre has low loss for wavelengths greater than 1350 nm, with some absorption features like a bulk aerogel. The transmission slowly decreases for

wavelengths down to 750 nm, and the noisier line below 1350 nm suggests multiple modes beating together. Transmission is low for visible wavelengths, with an enhancement between 475 – 575 nm which (see below) is probably due to the bandgap.

To interpret the spectral results we simulated an idealized infinite cladding using a fixed-frequency plane-wave solver [11]. Cladding dimensions were estimated from the SEMs in Fig. 2 then adjusted slightly until the simulated bandgap matched that measured in the actual unfilled fibre. This compensates for uncertainties in SEM measurements. The photonic density of states (DOS) is shown in Fig. 4(b) with the bandgap for the index of air marked by the arrowed line.

The upper edge of non-zero DOS is the effective index of the cladding. At wavelengths longer than ~900 nm, where the effective index is below the aerogel index of 1.045, the aerogel-filled core can guide by total internal reflection. We also see that the intersection of the bandgap with the core index is blue-shifted for an aerogel core compared with an air core. The experimental plot shows both these features: a (lossy) shifted bandgap and broadband guidance at long wavelengths. However, a more accurate simulation including the core wall is required to explain the transition between the two.

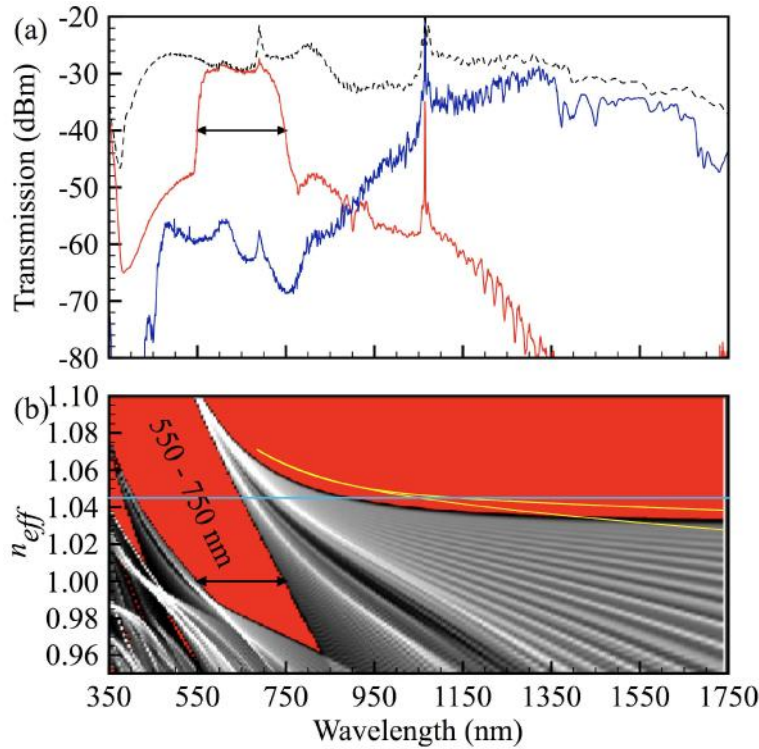


Fig. 4. (upper) Measured spectra of supercontinuum source (grey, dashed), unfilled fibre (red) and aerogel-filled fibre (blue). The peak at 1064 nm is the residual pump. (lower) Simulated DOS of the fibre's cladding. Lighter shades of grey represent higher DOS, while red means no cladding states are supported (zero DOS). The blue line marks the aerogel index $n = 1.045$. Yellow lines are guided modes of the filled fibre.

4. Modes

The output near-field pattern at 1540 nm measured by the InGaAs camera shows a Gaussian-like fundamental mode in the core, which we call the 'aerogel mode', Fig. 5. Simulation using a computational super-cell to include a core predicts that the waveguide is single-mode (bar polarisation degeneracy) at this wavelength. At shorter wavelengths within the index-guided

regime, light begins to recede into the glass core-surround, particularly to the ‘fatter’ pieces of glass at the boundary. Figure 5 shows this trend in both measured and calculated modes.

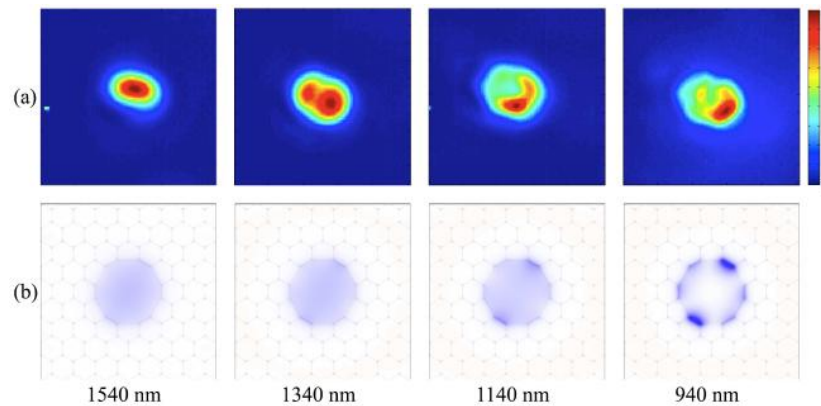


Fig. 5. (a) Measured near-field images of the filled fibre at four wavelengths. (b) Simulated mode patterns at the same wavelengths (within 10 nm), superimposed on the simulated structure.

The calculated effective index of the aerogel mode is the upper yellow line in Fig. 4(b). The lower yellow line is the first higher-order mode, which is concentrated in the core surround and which we call the ‘core surround mode’. These mode indices converge, and actually cross, as wavelength decreases and the aerogel mode migrates to the core surround. The crossing is not forbidden as the modes have different symmetries; the core surround mode has a TE_{01} -like vector direction whereas the aerogel mode is HE_{11} -like.

Within the bandgap, imaging the near-field at 550 nm (using a Si CCD camera) produces a complex pattern that is very sensitive to small changes in the launch optics. This is typical of a multimode waveguide, and not surprising given that the bandgap ‘pit’ in Fig. 4 is deep enough (1.045-1.00) to support many modes.

The localisation of modes to the glass core-surround allows them to have higher effective indices than the aerogel. This extends index guidance, albeit with higher loss, to shorter wavelengths that overlap with the long-wavelength edge of the bandgap pit. Indeed at 750 nm we observed two distinct guided modes, Fig. 6. The first was localised in the core surround, presumably guided by total internal reflection. The second was concentrated in the aerogel with a high spatial frequency and hence a low effective index, presumably guided by the bandgap. If our interpretation is correct then we believe this to be the first observation of coexisting index- and bandgap-guided modes.

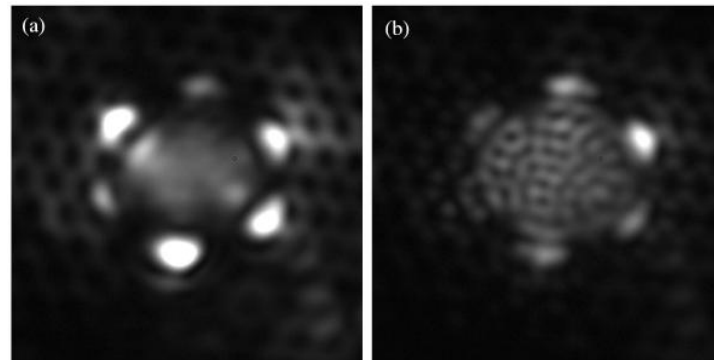


Fig. 6. Output near-field images, for 750 nm light coupled into the filled fibre with a $40\times$ objective, of (a) an index guided mode and (b) a bandgap guided mode (with apparently a small amount of the index guided mode). The modes were selected by adjusting the input coupling.

5. Conclusion

We have filled a hollow-core PCF with aerogel of refractive index 1.045 by sucking sol into the core and supercritically drying it. The linear refractive index properties have been investigated optically and compared to modelling, with good quantitative agreement. For wavelengths longer than 1400 nm, light is guided in the aerogel core in a single mode by total internal reflection, despite the very low index of the aerogel. The attenuation at 1540 nm was 0.2 dB/cm, comparable to that of the bulk aerogel. At shorter wavelengths the mode becomes concentrated in the core surround before index guidance fails completely, though bandgap guidance is still possible. There is evidence of coexisting index- and bandgap-guided modes.

It is interesting to note that, given the low refractive index and reported high nonlinearity of the aerogel, even quite modest pulsed lasers could cause a significant change to the properties of the waveguide. This would be even more striking if the sign of the nonlinearity is negative, as reported by Seo et al [3]. A peak-power less than 1 kW would depress the core index below that of the cladding, inducing a large amount of loss in the fibre.

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